A SUMMARY OF PERFORATED WALL
WIND TUNNEL STUDIES
AT THE
ARNOLD ENGINEERING DEVELOPMENT CENTER

By

M. Pindzola and W. L. Chew
PWT, ARO, Inc.

August 1960

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ABSTRACT

A summary of the work done at AEDC in the development
of perforated walls for application to transonic and supersonic
wind tunnels is presented. Results are summarized for nor-
mal, slanted, and slotted hole walls in the Mach number range
from 0.90 to 2.50. The slotted hole data, presented for the
first time, indicate that the characteristics of a perforated
wall can be determined independently of the free-stream Mach
number.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

C_p	Pressure coefficient, $(p - p_\infty)/q_\infty$
$(C_p)_w$	Wall pressure coefficient, $(p_\infty - p_c)/q_\infty$
C_{p_θ}	Slope of the pressure coefficient versus flow inclination (characteristic) curves
M	Free-stream Mach number
p	Local static pressure
p_c	Plenum chamber static pressure
p/p_t	Ratio of local static pressure to free-stream total pressure
p_∞	Free-stream static pressure
q_∞	Free-stream dynamic pressure
x/d	Distance from model nose normalized by the body diameter
θ	Flow inclination relative to the free-stream direction, radians

INTRODUCTION

In 1948 the NACA (Ref. 1) demonstrated that a wind tunnel with partially open test section walls could be used not only for extending the choking Mach number of a subsonic tunnel but also for testing at and above a Mach number of 1.0. In later studies at Cornell (Ref. 2), a wall with discrete openings instead of longitudinal slots was used for the same purpose.

The satisfactory cancellation of two-dimensional shock waves was demonstrated at UAC in 1951 (Ref. 3) by using a wall with discrete openings drilled normal to the test section walls. In these studies, optimum results were obtained with walls in which the ratio of open to total area was 22 percent. Later studies at the Ohio State University (Ref. 4) and the Arnold Engineering Development Center (AEDC) (Refs. 5 through 8) demonstrated the effectiveness of walls of this porosity in the cancellation of the bow shock from a three-dimensional model as well. These studies were used as a basis for design, and the initial set of walls for the 16-Foot Transonic Circuit of the Propulsion Wind Tunnel (PWT) at the AEDC was fabricated with this geometry (see Ref. 9).

In an effort to improve the expansion wave cancellation qualities of the 22-percent normal hole wall, investigations were initiated in the 1-Foot Transonic Tunnel at the AEDC in 1954. These studies led to the development of a wall of 6-percent porosity in which the perforations were slanted 60 deg from the normal. As shown in Refs. 10 through 13, significant improvements were attained in the reduction of the expansion wave reflections from the test section walls while good compression wave cancellation properties were retained, particularly at Mach numbers near 1.20.

Work was continued in the Mach number ranges from 0.95 to 1.15 (Refs. 14, 15, and 16) and above 1.20 (Refs. 17, 18, and 19) to determine the porosity requirements for the slanted hole wall at other than a Mach number of 1.20. These requirements were shown to decrease below a Mach number of 1.20 and increase above this Mach number.

An effort was then made to reduce the Mach number dependence of the wall by the use of slotted holes. This report presents the results of this effort as well as a summary of the previous studies conducted at the AEDC.

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THEORETICAL CONSIDERATIONS

The theoretical studies performed during the AEDC investigations were primarily concerned with predicting the wall characteristics required to provide an interference-free boundary. In the course of these studies, interference-free pressure distributions were obtained on various models to serve as a basis for the evaluation of the test results. Some theoretical work was also done in predicting the characteristics of walls of various hole shapes. This information was used as a guide in the selection of the various wall configurations to be tested.

REQUIRED WALL CHARACTERISTICS

To obtain the required characteristics of the test section walls, the flow fields about the experimental test models were first calculated. Characteristics were then obtained by calculating the flow conditions along a line parallel to the free-stream flow direction at a distance from the model corresponding to the position of the wall.

For purely supersonic Mach numbers, where the bow shock is attached to the model, the flow field conditions were obtained by the method of characteristics (see Ref. 11). A typical example of these conditions showing the pressure coefficient plotted versus the flow angle is presented in Fig. 1 for a 20-deg cone-cylinder model of 2-percent blockage at a Mach number of 1.5. The values of the pressure coefficient and flow angle represent the conditions existing in the flow field at a position corresponding to the tunnel wall. With the assumption that the average flow conditions are described by a line joining the extremes of such curves, Fig. 2 was prepared to indicate the influence of Mach number on the required wall characteristics.

An approximation of the required characteristics at transonic Mach numbers was obtained in Ref. 16 for a parabolic-arc body of revolution using supersonic linearized theory. The results for a model of 2.8-percent blockage are shown in Fig. 3. In both Figs. 2 and 3 the slope of the curves decreases as Mach number is increased.

PREDICTED CHARACTERISTICS OF PERFORATED WALLS

Various investigators have made analytical studies of the flow through perforated walls in an effort to predict their behavior (see Refs. 13, 18, 20, and 21). These studies have met with limited success, however,

because of the many parameters, such as the boundary layer thickness, hole shape, and wall thickness, which influence the flow through the walls. In general, therefore, it has been found necessary to obtain the actual wall characteristics by experimental means such as presented in a later section on experimental wall characteristics.

In some cases it is possible to obtain a qualitative picture of the test results from the theoretical studies. This is exemplified by the reasoning which led to the use of the slotted hole. With the assumption that the perforated wall acts as a series of wings at a small angle of attack, as suggested in Ref. 20, the Mach number dependence of the wall was essentially eliminated by use of the slotted hole, as will be discussed later in this report.

REFERENCE PRESSURE DISTRIBUTIONS

At Mach numbers above 1.20, theoretical surface pressure distributions on the test model are used as a basis for comparison and evaluation of the experimental data. These distributions were obtained in the process of calculating the flow field conditions used to specify the required wall characteristics. The accuracy of these curves as base plots was checked by obtaining test data in a tunnel where the model was well within the test rhombus. Excellent agreement was obtained.

For Mach numbers below 1.20, interference-free data for the test model were obtained from tests conducted in the 16-Foot Transonic Circuit of the PWT. Since the model was 1.915 inches in diameter, representing a blockage ratio of 0.008 percent in the large circuit, the data are believed to be free of interference from the test section walls.

EXPERIMENTAL WALL CHARACTERISTICS

During the studies at AEDC, experimental wall characteristics were obtained for a wide variety of perforated test specimens. Results presented in this report, however, are limited to the three configurations shown in Fig. 4, i.e., the 22-percent normal, the 6-percent slanted, and the 10-percent slotted hole walls.

The results presented in this section were obtained in the 1-Foot Transonic Tunnel. The tunnel configuration (see Fig. 5) consisted of a 3.5 by 9 inch test sample mounted on a specially fabricated movable top wall. A secondary plenum chamber was used to isolate the flow through

the test sample. Flat plate orifices were used in the secondary plenum chamber evacuation line to measure the total flow rate through the sample. Mach numbers up to and including 1.0 were established in the test region with a sonic nozzle in conjunction with auxiliary suction. Supersonic Mach numbers over the test sample were established with a flexible Laval nozzle and suction. The boundary layer thickness approaching the test sample was held constant by convergence of the top and bottom test section walls.

The cross flow characteristics are presented as plots of pressure coefficients versus the flow deviation angle at the test specimen. The pressure coefficient, $(C_p)_w$, was obtained as a difference between free-stream static pressure and the static pressure in the secondary plenum chamber divided by the free-stream dynamic pressure. The flow deviation angle, θ, was obtained as a ratio between the rate of flow per unit surface area of the test sample and the rate of flow per unit cross-sectional area of the free stream.

The wall characteristics for the normal, slanted, and slotted hole walls are shown in Figs. 6 through 8, respectively. The significant features of the characteristics are pointed out in the following paragraphs.

The characteristics of the normal hole wall (Fig. 6) show that a slight outflow (positive θ) is obtained with zero pressure differential across the wall. The wall offers more resistance to outflow from the test section than for flow from the surrounding plenum into the test section.

The most pronounced effects of slanting the perforations through the wall (Fig. 7) are first, to shift the characteristics to where outflow is maintained with a pressure coefficient as low as -0.04 and second, to increase the resistance to inflow to values more nearly required for expansion wave cancellation. A definite Mach number effect on the characteristics is noted for both the normal and slanted hole configurations.

By slotting the holes in the direction of the airflow (Fig. 8), the Mach number dependence of the wall is essentially eliminated. The resistance to outflow, however, is greater than the resistance to inflow.

COMPARISON OF REQUIRED AND EXPERIMENTAL WALL CHARACTERISTICS

Comparisons of the required wall characteristics for a 2-percent blockage, 20-deg cone-cylinder model with the actual characteristics of the 22-percent normal, 6-percent slanted, and 10-percent slotted hole walls are shown in Fig. 9. The C_{p_θ} values for the curve labeled "required"

are twice the value of the slopes of the characteristic curves presented in Fig. 2. The assumption is made that the pressure differential available to exhaust the stream mass flow is twice that existing behind the disturbance wave in the free stream because of the added strength of the wave reflection. The data points for the various wall specimens represent the slopes of the characteristic curves presented in Figs. 6, 7, and 8 as well as higher Mach number data as presented in Ref. 18. Slopes indicated by the solid symbols were obtained in the region of outflow and those indicated by the open symbols, in the region of inflow at opposite extremes of the characteristic curves.

From these plots it can be seen that for Mach numbers below 1.6, the actual trend in the wall characteristic parameter with Mach number for the normal and slanted hole walls in the region of outflow is in direct disagreement with the required trend. By decreasing the slope of the characteristic curve for the slotted hole wall in the region of outflow, this wall would appear to offer some advantage over the others. A definite improvement in the inflow characteristics of the slanted hole wall over that of the normal hole wall is noted. The slotted hole wall also shows some improvement as the Mach number is increased above 0.9. These results tend to verify the suggestion that the perforated wall acts as a series of wings at small angles of attack. As is well known, the lift of a high aspect ratio wing increases with increasing Mach number in the subsonic speed range and decreases in the supersonic range. This Mach number dependence falls off, however, as wing aspect ratio is reduced. With this background, it was reasoned that a wall with transverse slots rather than round holes would provide the proper characteristics in the Mach number range above 1.0. Such a wall was therefore investigated and found to have a characteristic opposite to that predicted in the Mach number range from 1.0 to 1.4. It was then reasoned that the characteristics were governed by the Mach number at the wall rather than the free-stream Mach number. The Mach number at the wall was known to be approximately 0.7 of the free-stream value. A longitudinal slot was therefore tried, giving the Mach-number-independent results presented.

The data points at Mach numbers of 2.0 and 2.5 in Fig. 9 were determined from wall characteristics presented in Ref. 18. These characteristics were obtained in a different manner from those presented in Figs. 6 through 8. The technique employed was to measure the flow through all four walls of the perforated test section at various wall angles or, in effect, at various wall pressure coefficients. The data are therefore influenced to some extent by the resulting variations in boundary layer conditions over the plates at the different wall angles. As will be indicated later, the values of all of these results appear to be high. The data do follow the expected trend of a decrease in slope with an increase in Mach number.

EXPERIMENTAL MODEL TEST RESULTS

Wall interference studies have been made at AEDC using models of different shapes and various blockage ratios from 1/2 to 6 percent. The results of these tests are best exemplified by the data obtained with a cone-cylinder model of 2-percent blockage and 20-deg cone angle. Therefore, only these data are included in this summary report. The evaluation of the interference is made on the basis of comparisons between experimental pressure distributions on the surface of the model and the theoretical and interference-free data mentioned previously.

BASIC DISTRIBUTIONS

Pressure distributions on the model in the Mach number range from 0.95 to 2.00 are presented in Figs. 10, 11, and 12 for the 22-percent normal, 6-percent slanted, and a modified 10-percent slotted hole wall, respectively. The modification to the slotted hole consisted of slanting the leading edge of the slot to increase the open area exposed to the free stream as shown in Fig. 4c. The influence of the bow shock from the model on the body pressure distribution is confined primarily to the data points filled in solidly, whereas that of the expansion wave from the cone-cylinder junction is confined to the data points marked with a cross.

The data presented in Fig. 10 were obtained with test section walls of 22-percent porosity with normal holes. The cancellation of the model bow shock was satisfactorily achieved at a Mach number of approximately 1.3. Above this Mach number the wall was too closed, whereas below 1.3, the wall was too open for the shock disturbance. Throughout the Mach number range for which the data are shown, the wall proved to be too open for the expansion disturbance originating at the cone-cylinder junction.

Similar data are presented in Fig. 11 for walls of 6-percent porosity with slanted holes. Optimum shock cancellation is again obtained at a Mach number of approximately 1.30. Below this Mach number this wall was again too open, whereas above 1.30 the wall was too closed for the shock disturbance. Cancellation of the expansion disturbance, however, was much more satisfactory throughout the Mach number range with this wall.

The final set of basic distributions, presented in Fig. 12, was obtained with the modified slotted hole wall (see Fig. 4c). The wall modification was made to reduce the slope of the outflow characteristics of the basic slotted wall without affecting the inflow. The desirability of such a shift

is apparent in Fig. 9. In the range of Mach numbers from 1.2 through 1.5, the shock cancellation properties of the wall were satisfactory. Above a Mach number of 1.30, the expansion wave cancellation properties of the wall were also satisfactory. At a Mach number of 1.30 the effects of a disturbance from the reflection of the expansion wave are noticeable, and the effect becomes significant when the Mach number is decreased to 1.20.

EFFECTS OF WALL POROSITY

The effect of porosity on the cancellation properties of the normal and slanted hole walls is presented in Fig. 13. It is apparent that the character of the reflected disturbances can be changed significantly by a change in the effective wall porosity. The results show that the porosity requirements for acceptable shock cancellation with the normal hole wall (Fig. 13a) vary from 22 percent at a Mach number of 1.2 to 29 percent at a Mach number of 2.0. The optimum porosity for expansion wave cancellation in turn varies from 12 percent at 1.20 to 22 percent at 2.0. For the slanted hole wall (Fig. 13b), optimum wave cancellation is obtained with a wall porosity of slightly below 3 percent at a Mach number of 1.05, 6 percent at 1.2, and slightly below 12 percent at 2.0.

EFFECT OF WALL ANGLE

Typical effects of wall angle on the cancellation properties of the slanted and slotted hole walls at a Mach number of 1.30 are shown in Fig. 14. From these results, it can be seen that the character of the wave reflections can be altered significantly by wall angle changes.

DISCUSSION OF RESULTS

In the preceding sections, an attempt has been made to indicate the more important parameters which affect the wave cancellation properties of perforated walls. The effective porosity of the walls to both inflow and outflow is of course of prime concern, and it was shown that walls of various geometries can be made to produce either the proper outflow or the proper inflow conditions at any particular Mach number.

For a normal hole wall, the proper porosity for shock cancellation differed significantly from that required for expansion cancellation at any one Mach number. This situation was shown to be manageable with a

slanted hole wall at any one Mach number, but the porosity of such a wall had to be varied to obtain satisfactory shock cancellation results over a range of Mach numbers. Finally, tests of a slotted hole wall indicated some improvement in shock cancellation over a small Mach number range but not nearly enough to satisfy the requirements over the wide range of operation of the PWT. This later wall also appeared to lack the expansion cancellation properties of the slanted hole wall at the Mach numbers below 1.30.

Some measure of control of the cancellation properties of a fixed wall configuration is seen to be available by use of wall angle position. The effect is attributable to the differences in the boundary layer thickness at various wall angles and was first pointed out in Ref. 3. The range of control, however, again is not as large as required.

The walls for the PWT circuits, as a result of the AEDC studies, are of the slanted hole variety. A porosity of 6 percent was chosen for the transonic circuit test section walls, whereas for the supersonic circuit a porosity of 11 percent was selected. Since these walls are most effective at Mach numbers of 1.3 and 2.0, respectively, some measure of wall inter-ference must be accepted at other Mach numbers. A variation in wall angle can be used to minimize this interference. Small discrepancies in the data in the overlapping test range at Mach numbers from 1.5 to 1.6 must also be expected.

The results with the slotted hole indicate that the wall characteristics can be made independent of the free-stream Mach number. Although en-couraging, the wave cancellation properties of the wall are not considered superior to those with the slanted hole wall. A greater resistance to inflow is required at the lower Mach numbers. It is also believed that some method of retaining the pressure recovery characteristics of the slanted hole wall, wherein outflow is maintained at negative C_p values, is required at Mach numbers below 1.30.

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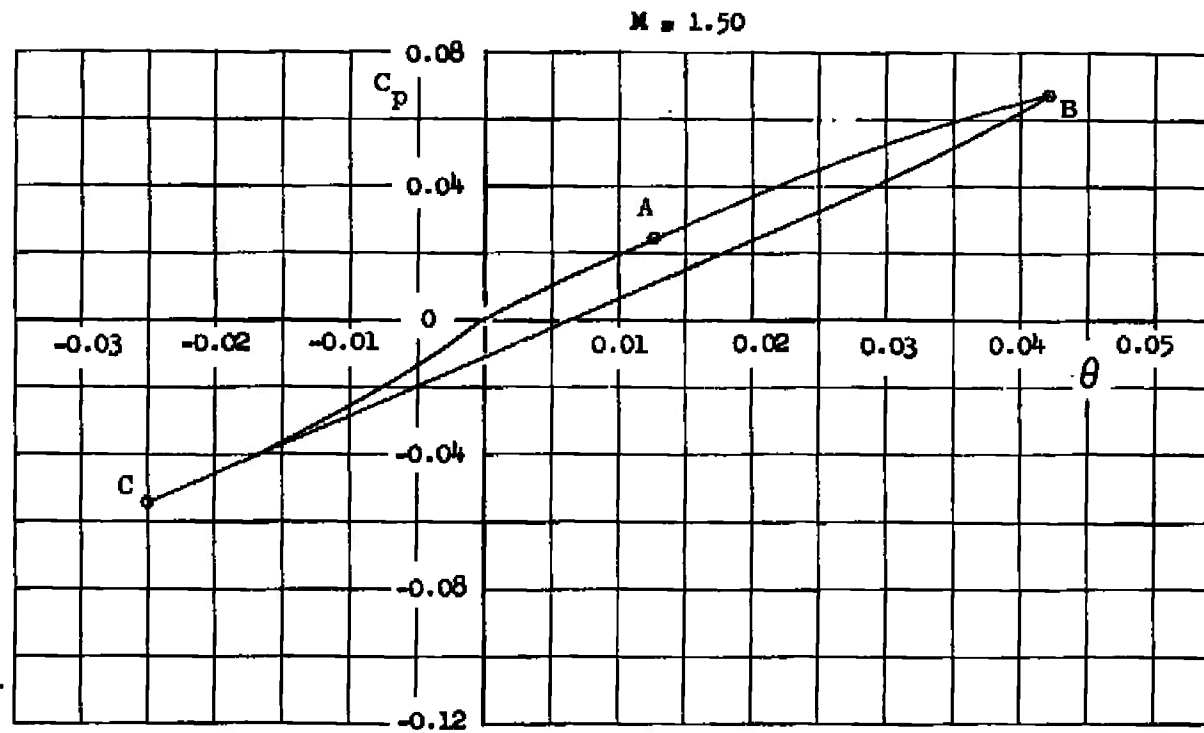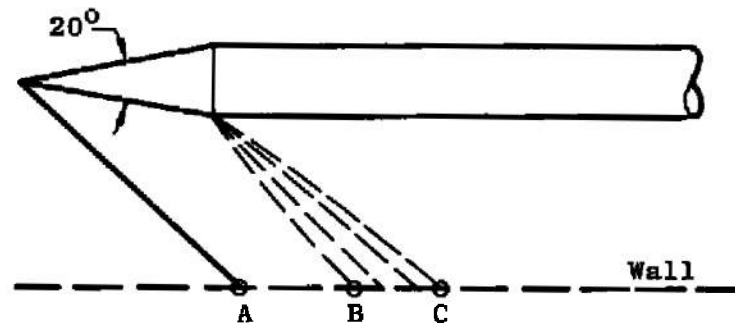
Fig. 1 Required Flow Characteristics in the Flow Field about a 20° Cone-Cylinder Model of 2-Percent Blockage at a Position Corresponding to the Tunnel Wall
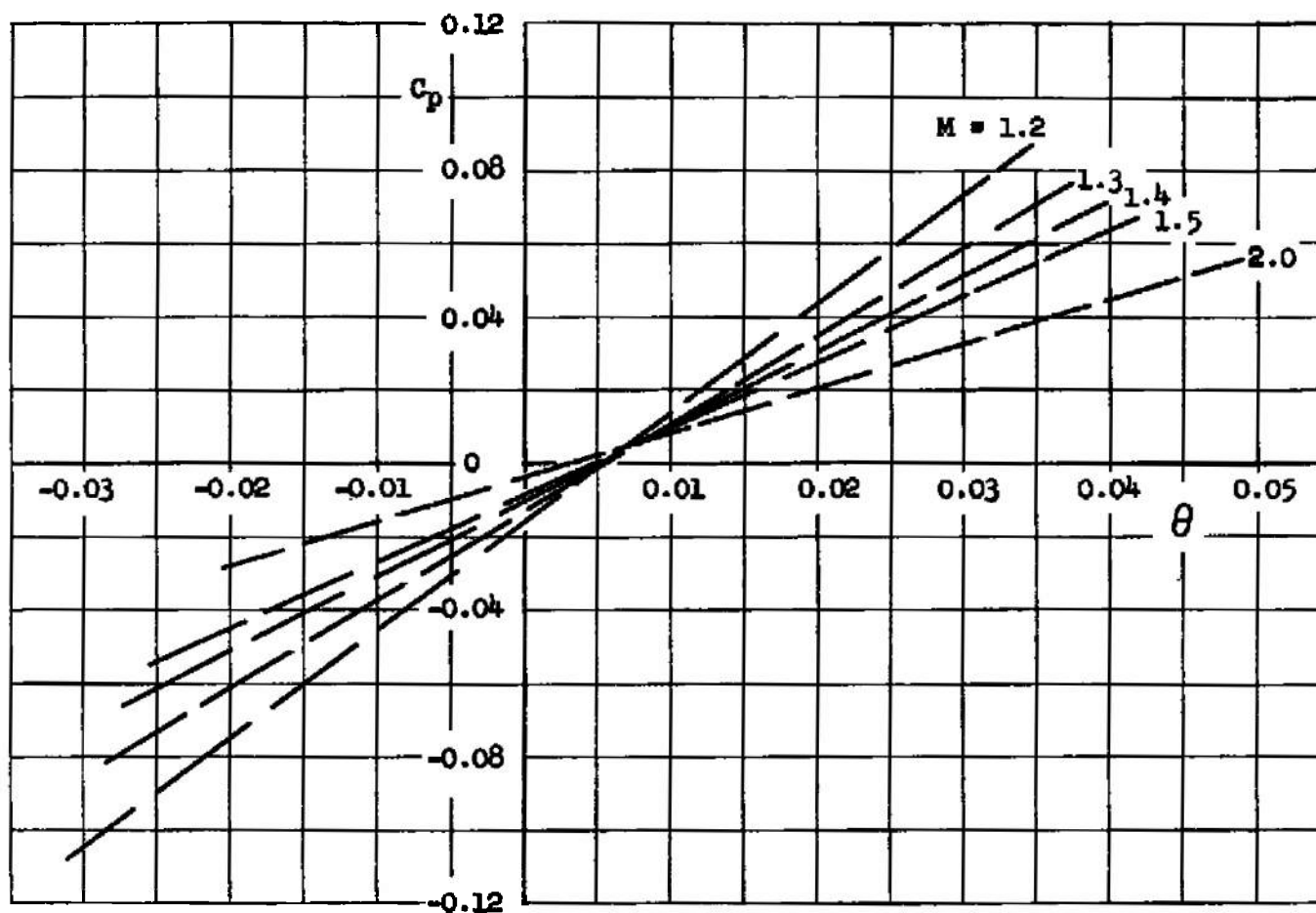
Fig. 2 Average Flow Characteristics in the Flow Field about a 20° Cone-Cylinder Model of 2-Percent Blockage at a Position Corresponding to the Tunnel Wall
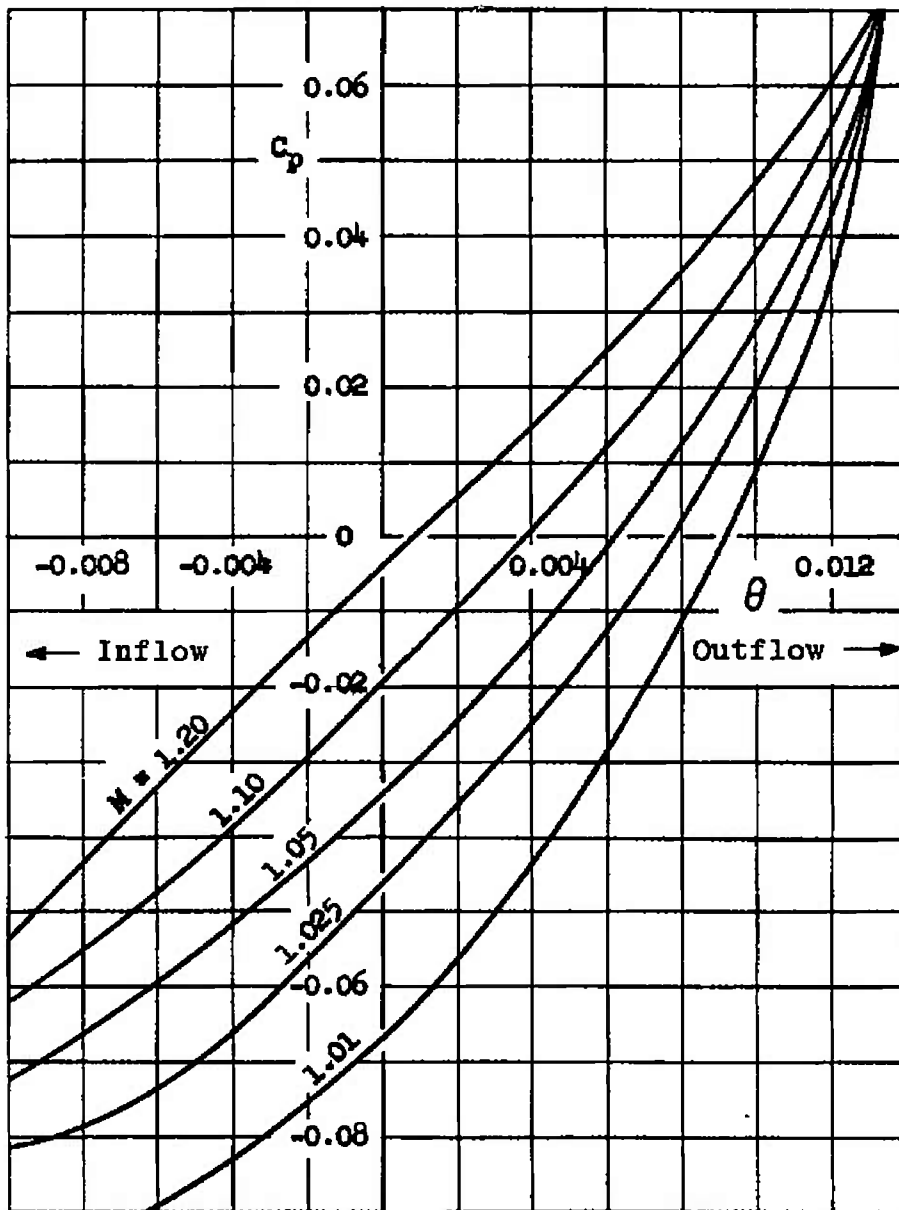
Fig. 3 Required Flow Characteristics in the Flow Field about a Parabolic-Arc
Body of Revolution of 2.8-Percent Blockage at a Position Corresponding
to the Tunnel Wall
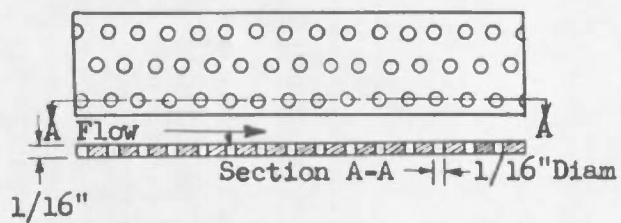
a. 22-Percent Normal
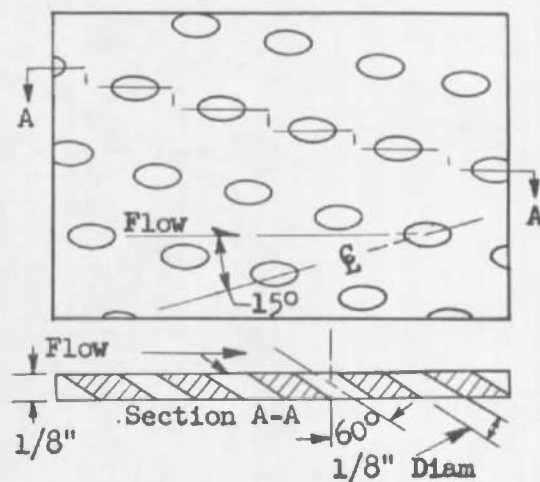
b. 6-Percent Slanted
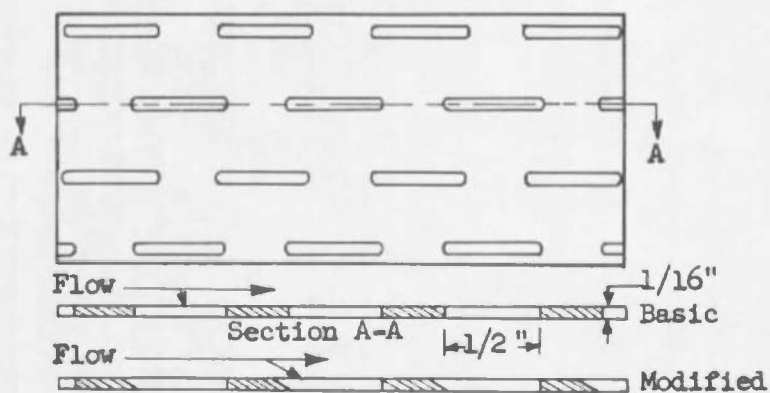
c. 10-Percent Slotted

Fig. 4 Schematic Layouts of the Perforated Walls
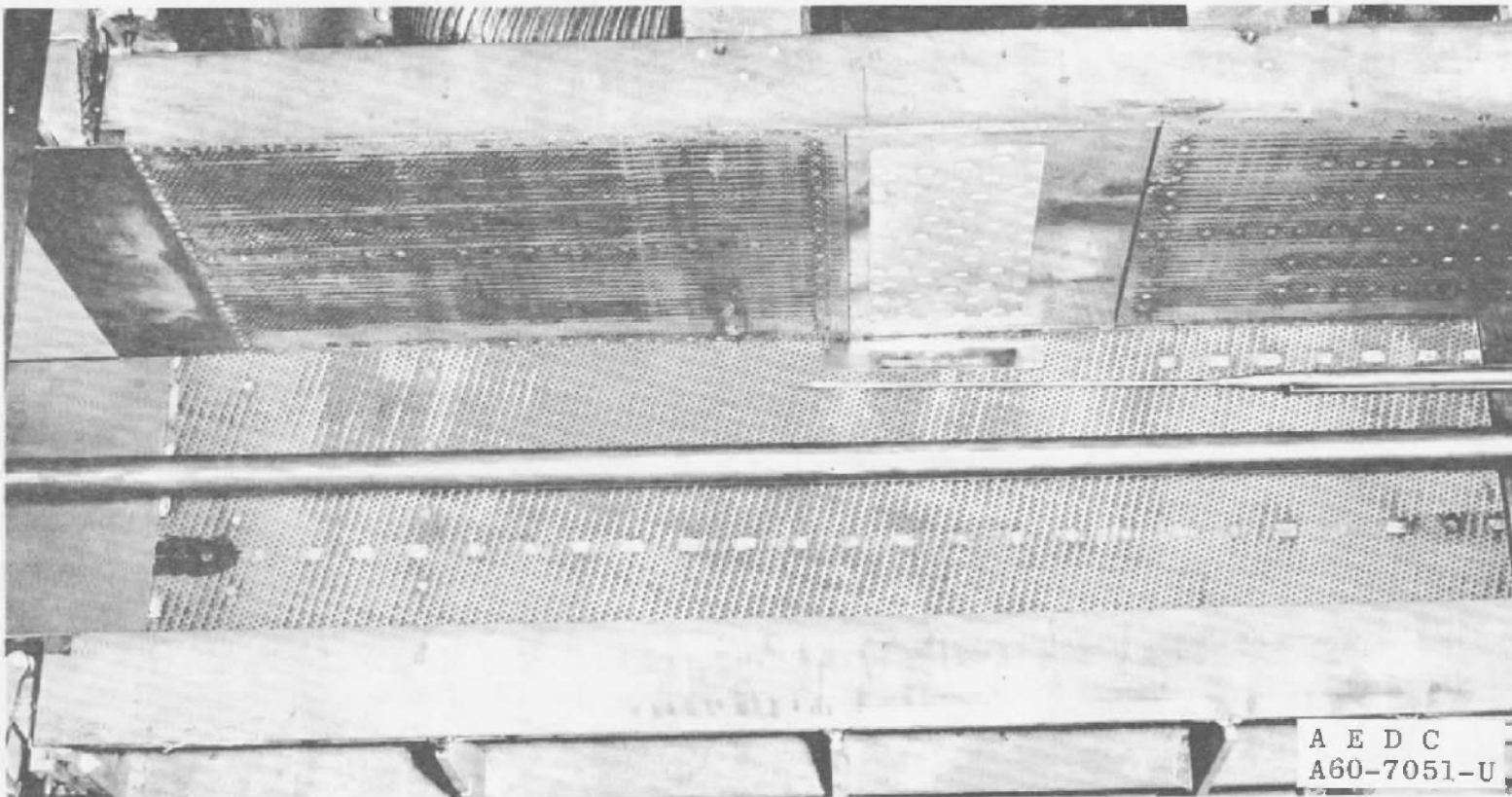
Fig. 5 Test Section Configuration for Wall Characteristic Study

Symbol	Mach Number
⊙	0.90
◇	1.20
△	1.40
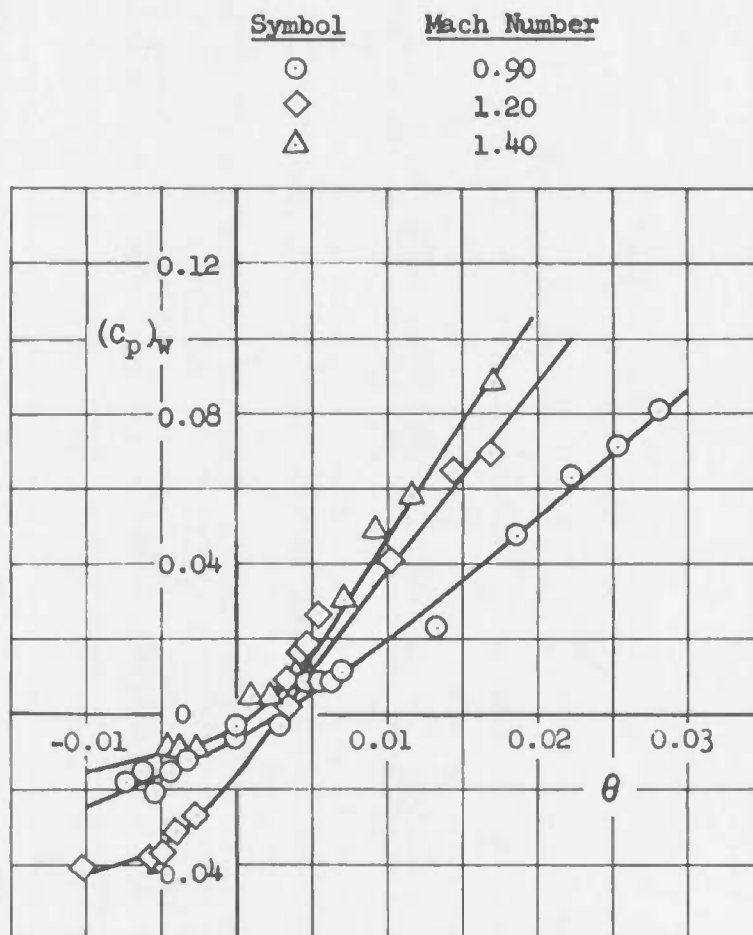
Fig. 6 Experimental Wall Characteristics for the 22-Percent Normal Hole Wall
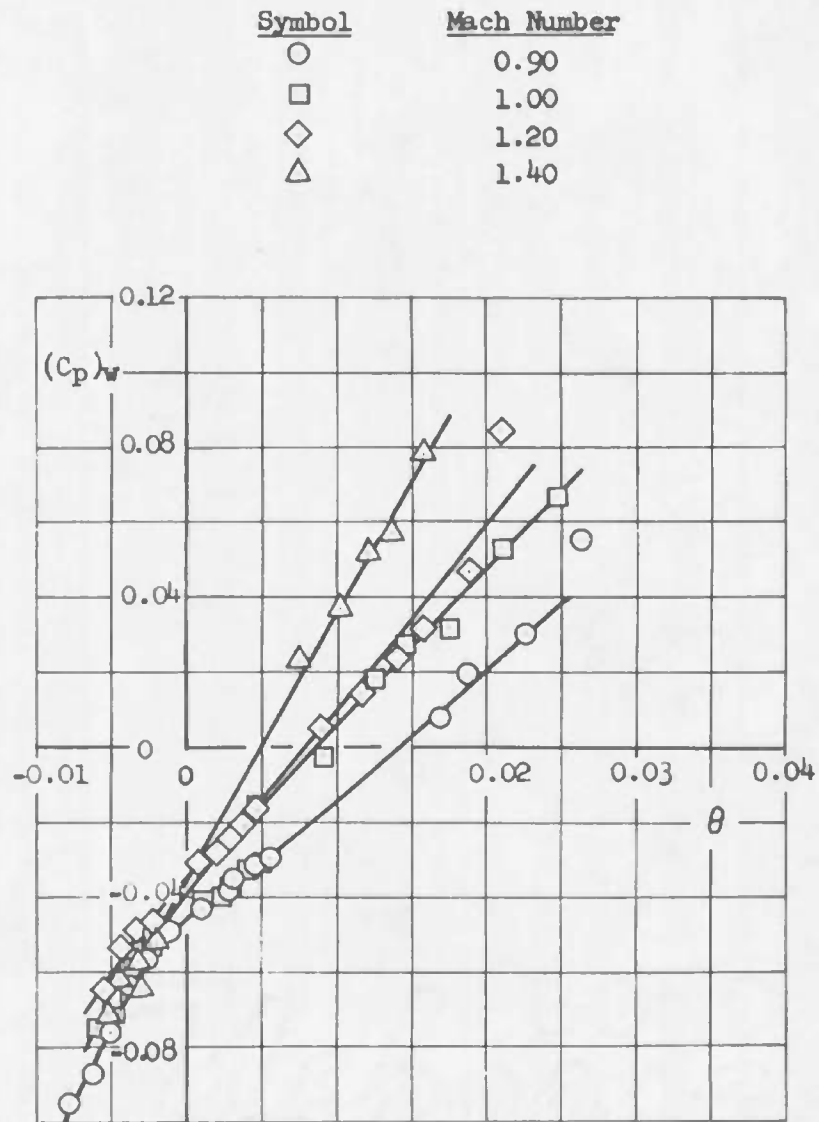
Fig. 7 Experimental Wall Characteristics for the 6-Percent
Slanted Hole Wall

Symbol	Mach Number
○	0.90
□	1.00
◇	1.20
◊	1.30
△	1.40
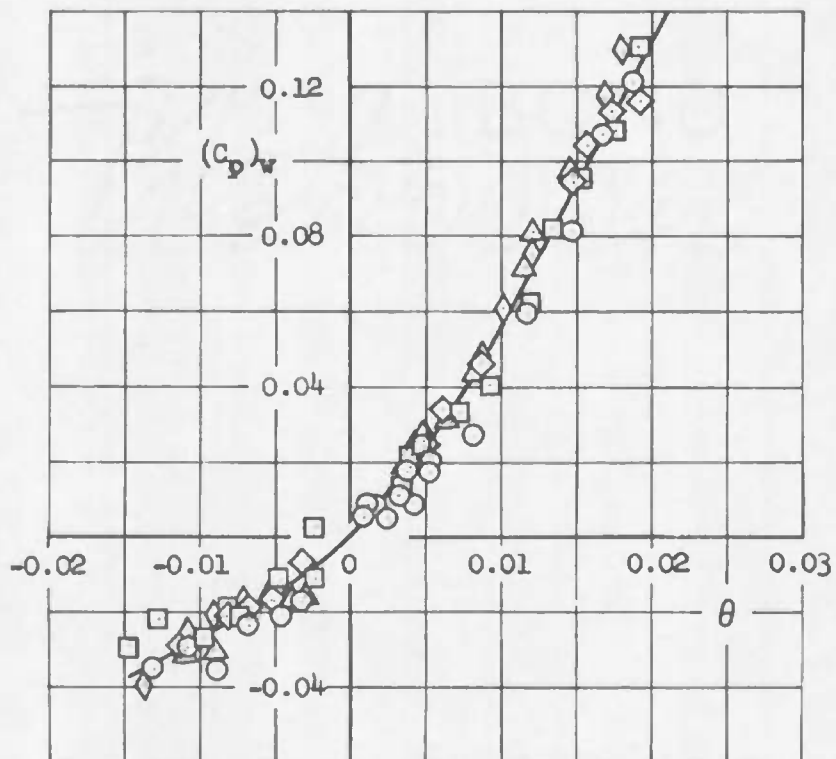
Fig. 8 Experimental Wall Characteristics for the 10-Percent
Slotted Hole Wall

23

Symbol   Wall

☐   Normal (22%)
◇   Slotted (10%) Non-Modified
○   Slanted (6%)
△   Slanted (12%)

Solid points show slopes in outflow region.
Open points show slopes in inflow region.
M = 2.0 and 2.5 data from Ref. 18 (no inflow
    data available).
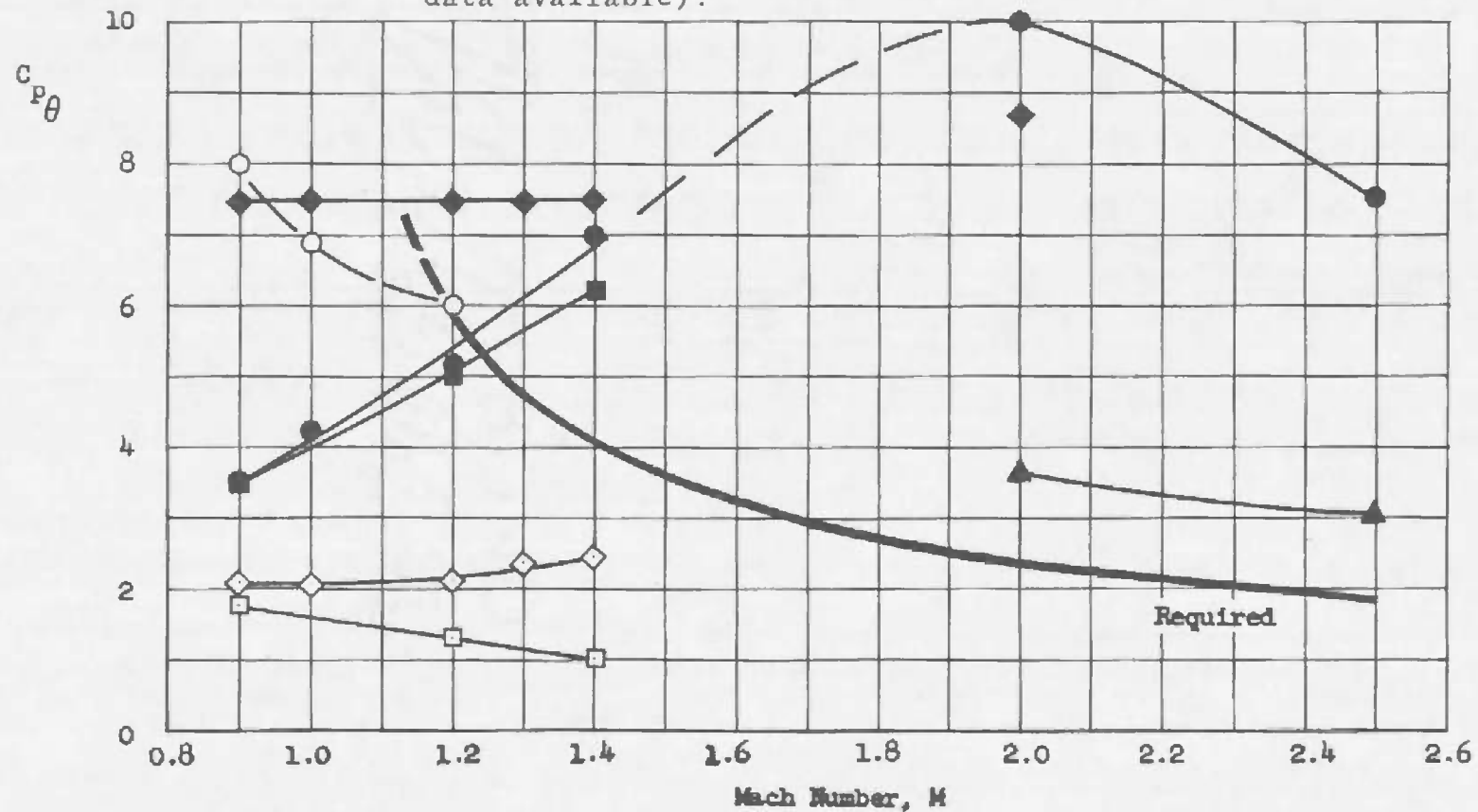
Fig. 9 Comparison of Required and Experimental Wall Characteristics
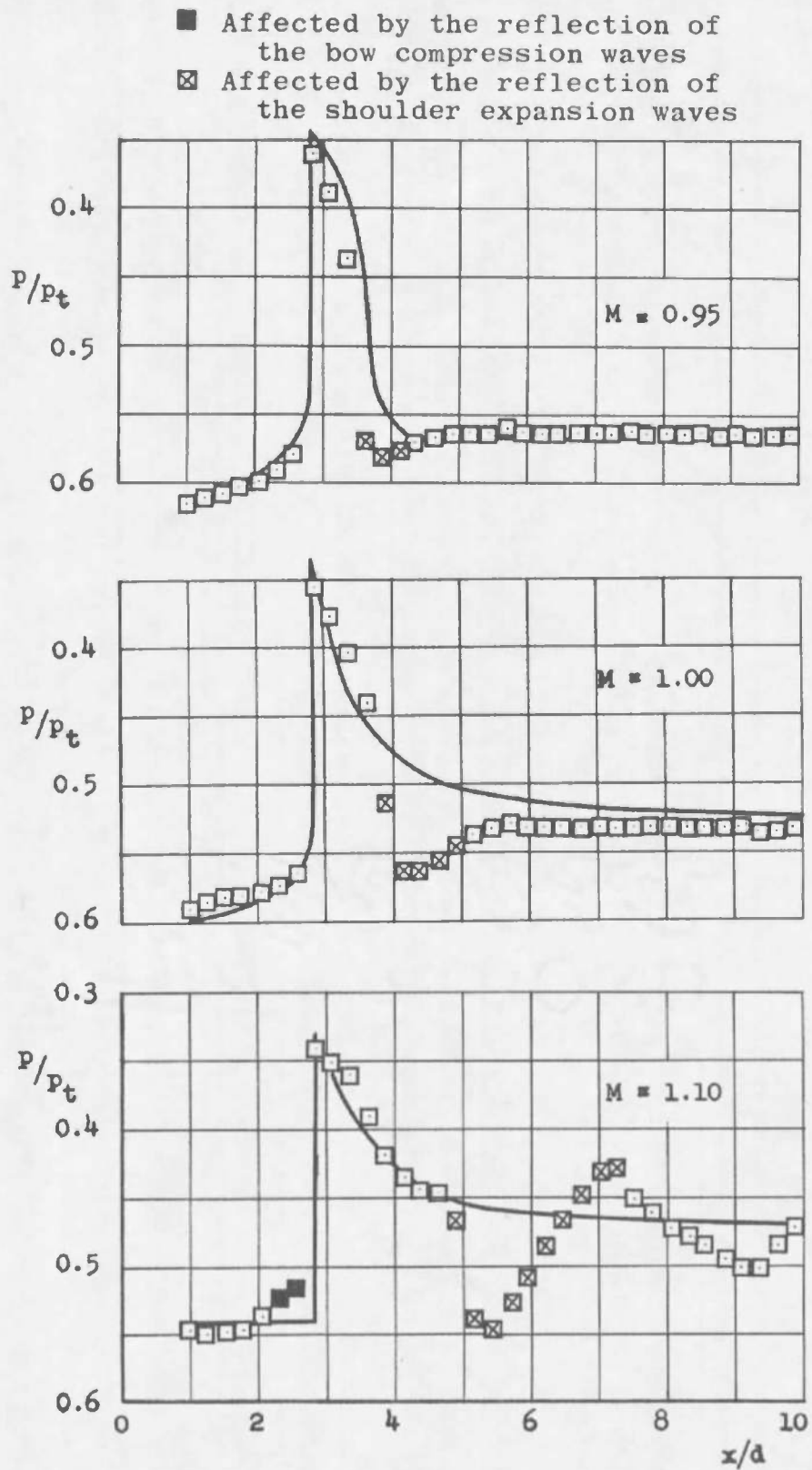
Fig. 10 Body Pressure Distributions on a 2-Percent Blockage, Cone-
Cylinder Model with 22-Percent Normal Hole Walls
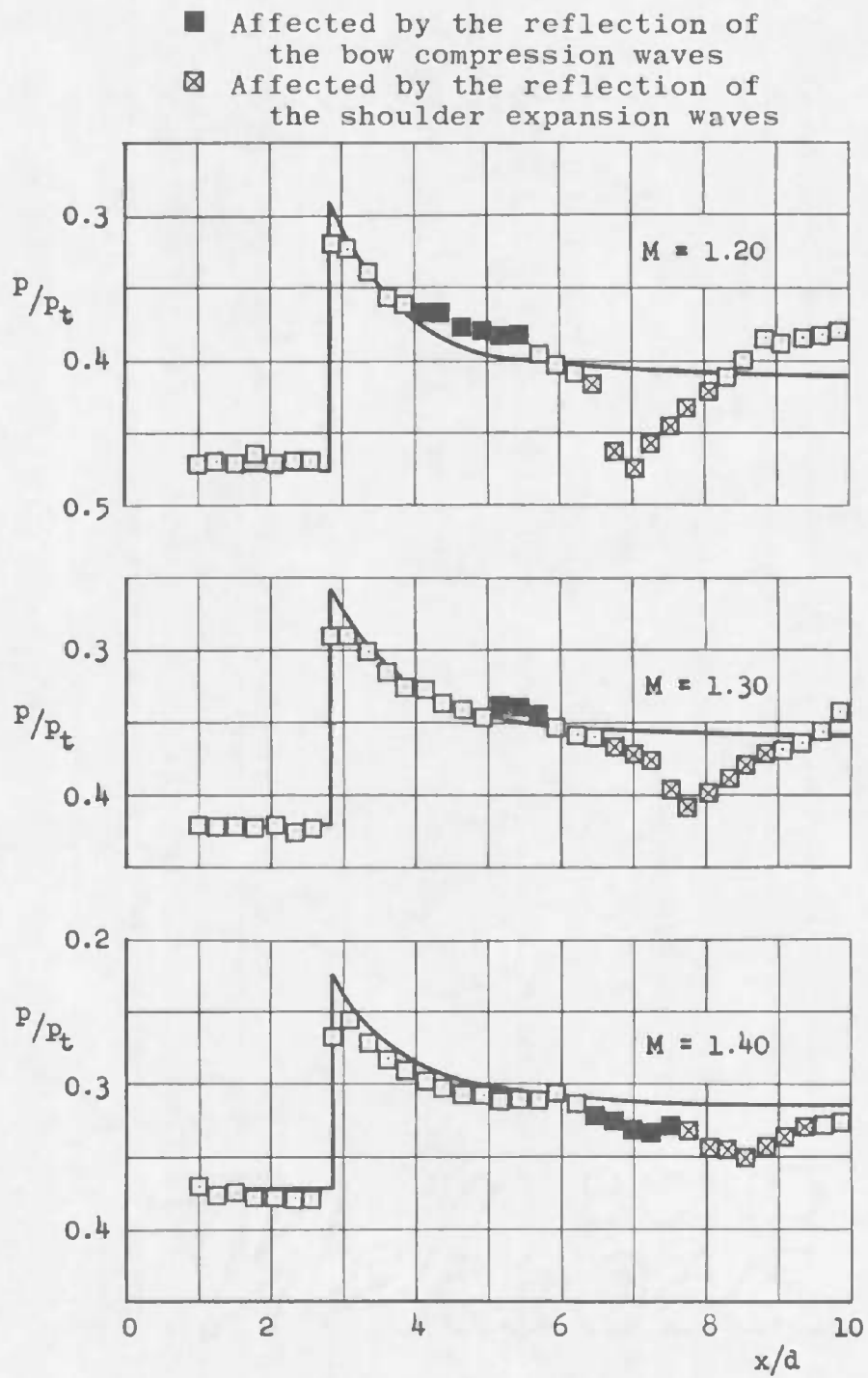
Fig. 10 Continued
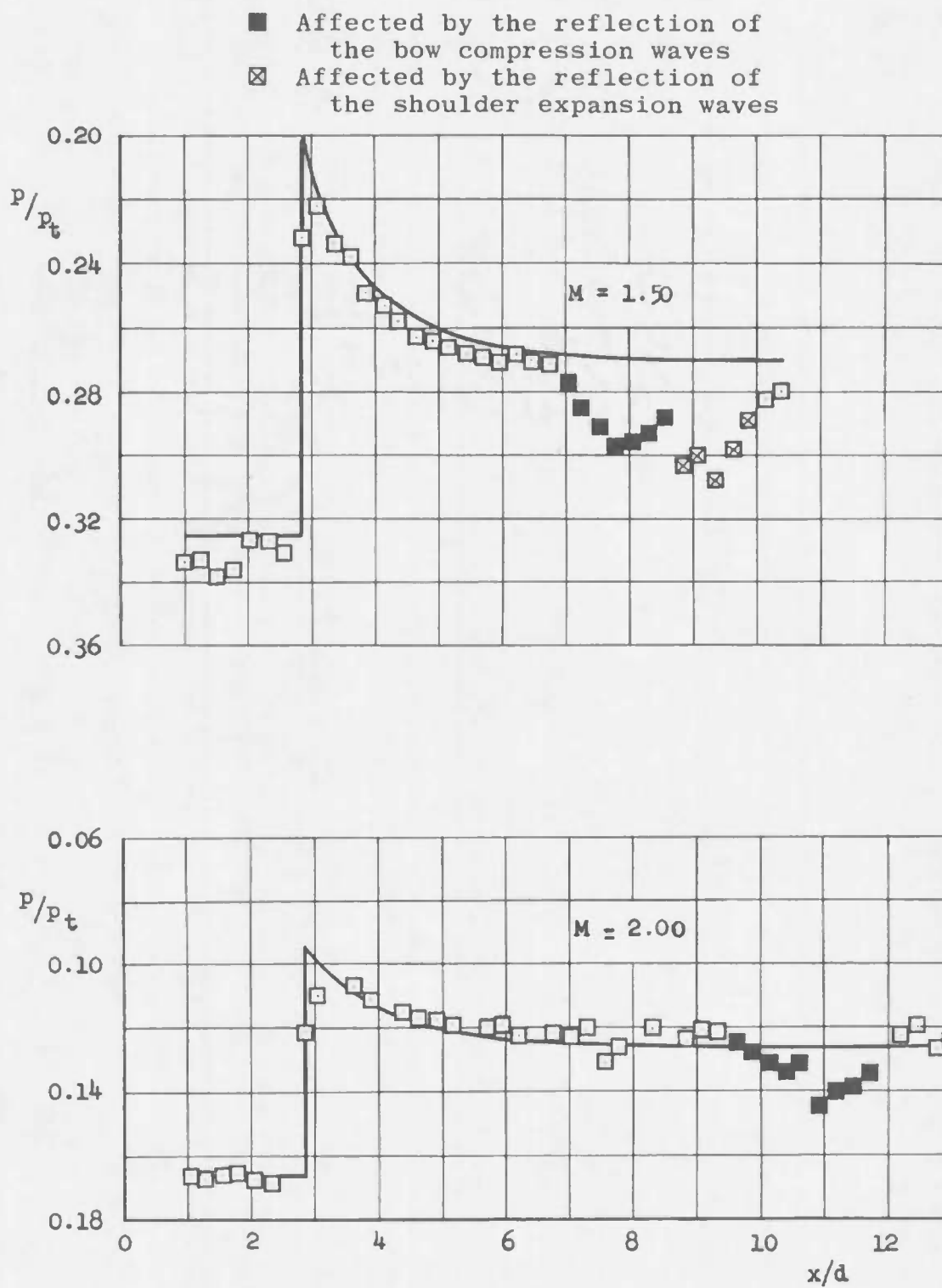
Fig. 10 Concluded
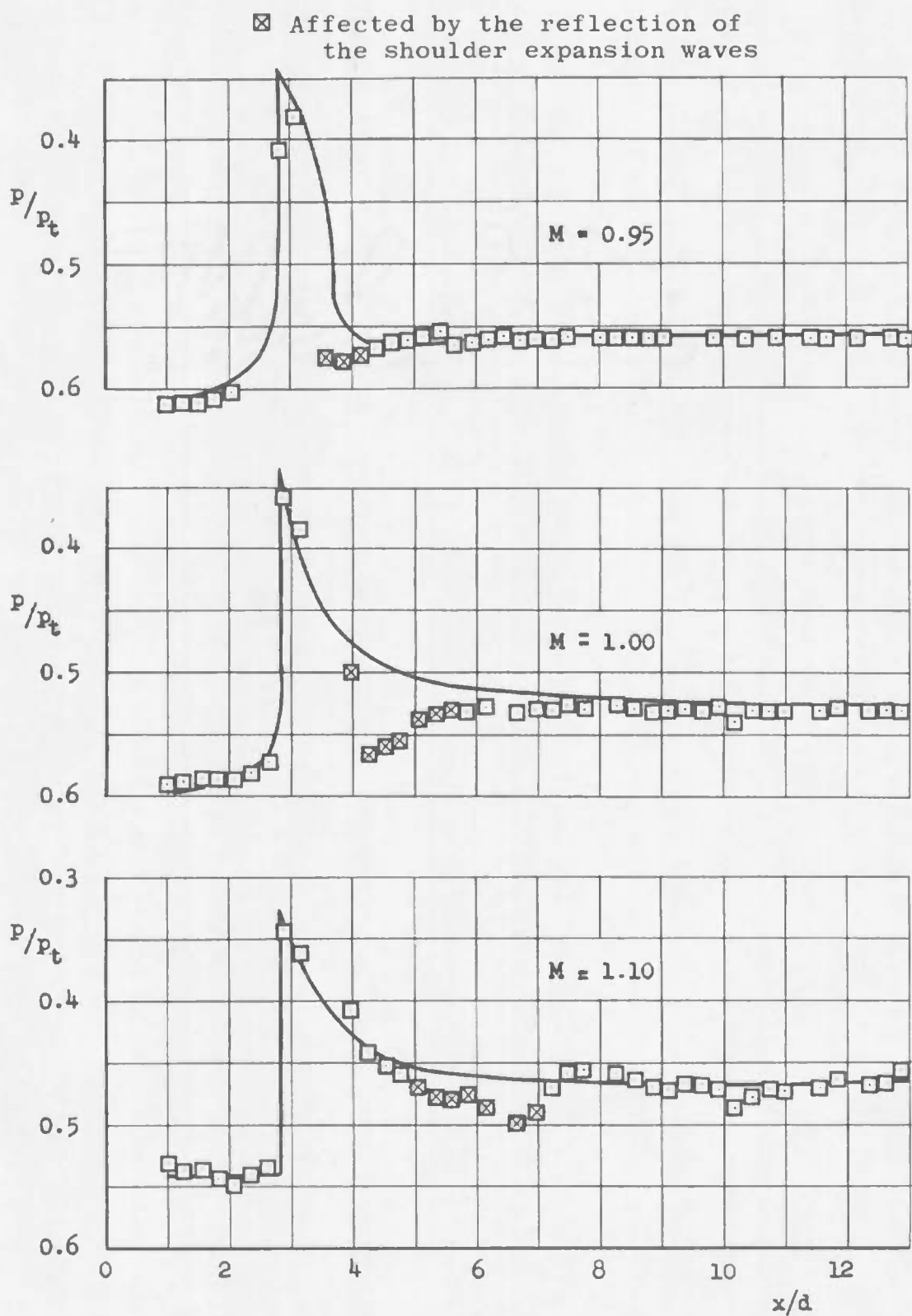
Fig. 11 Body Pressure Distributions on a 2-Percent Blockage, Cone-Cylinder Model with 6-Percent Slanted Hole Walls

28
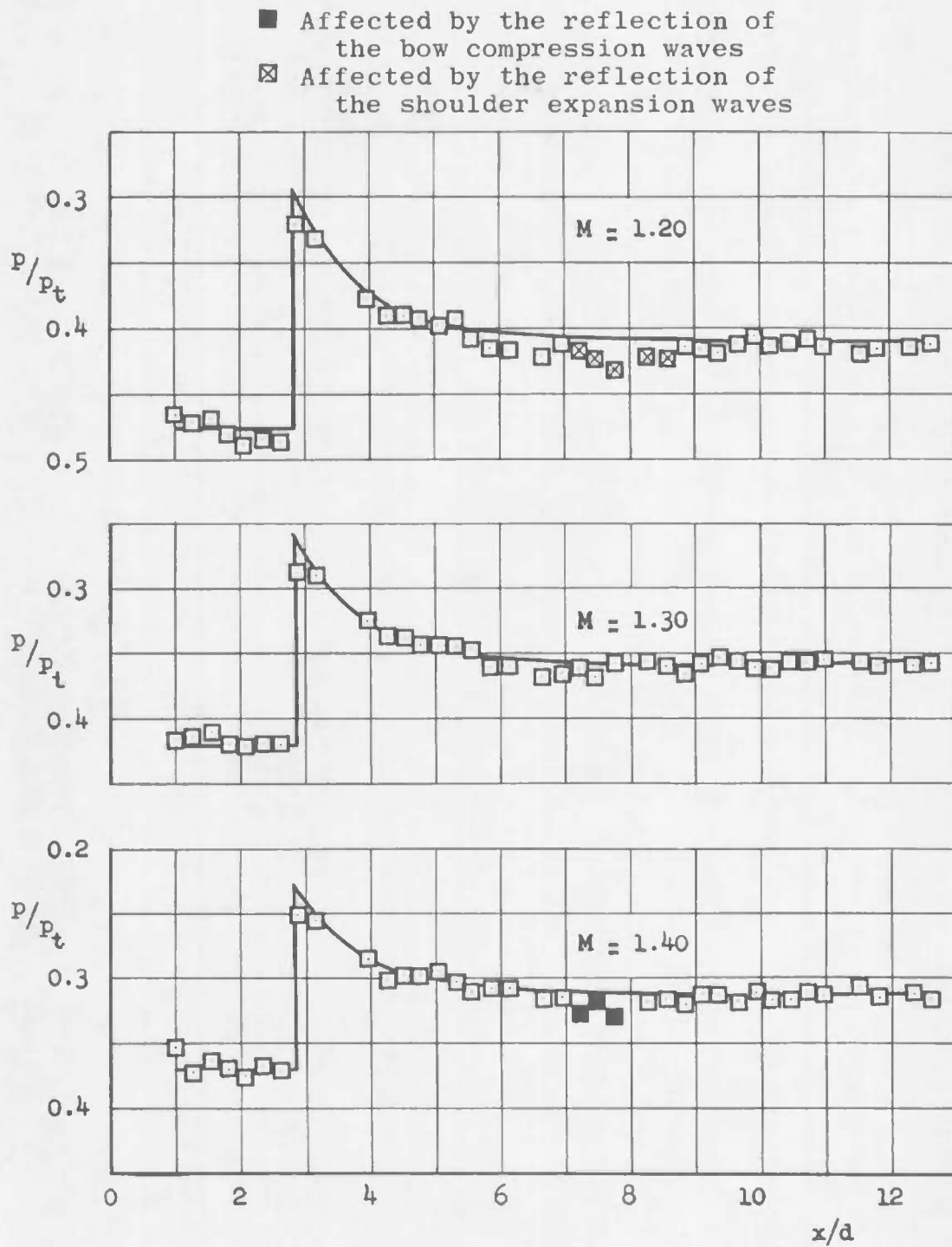
Fig. 11 Continued

Fig. 11 Concluded

⊠ Affected by the reflection of
the shoulder expansion waves
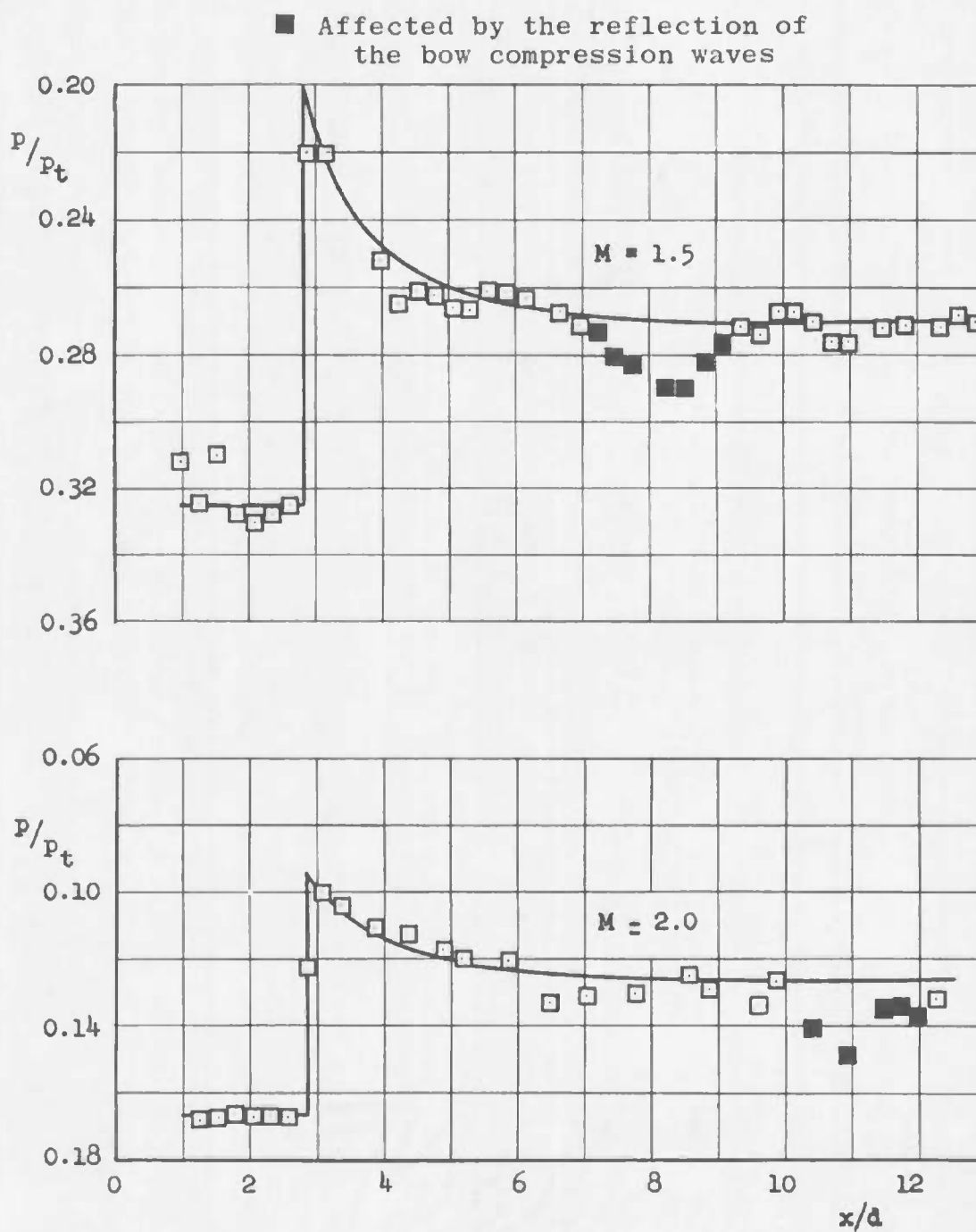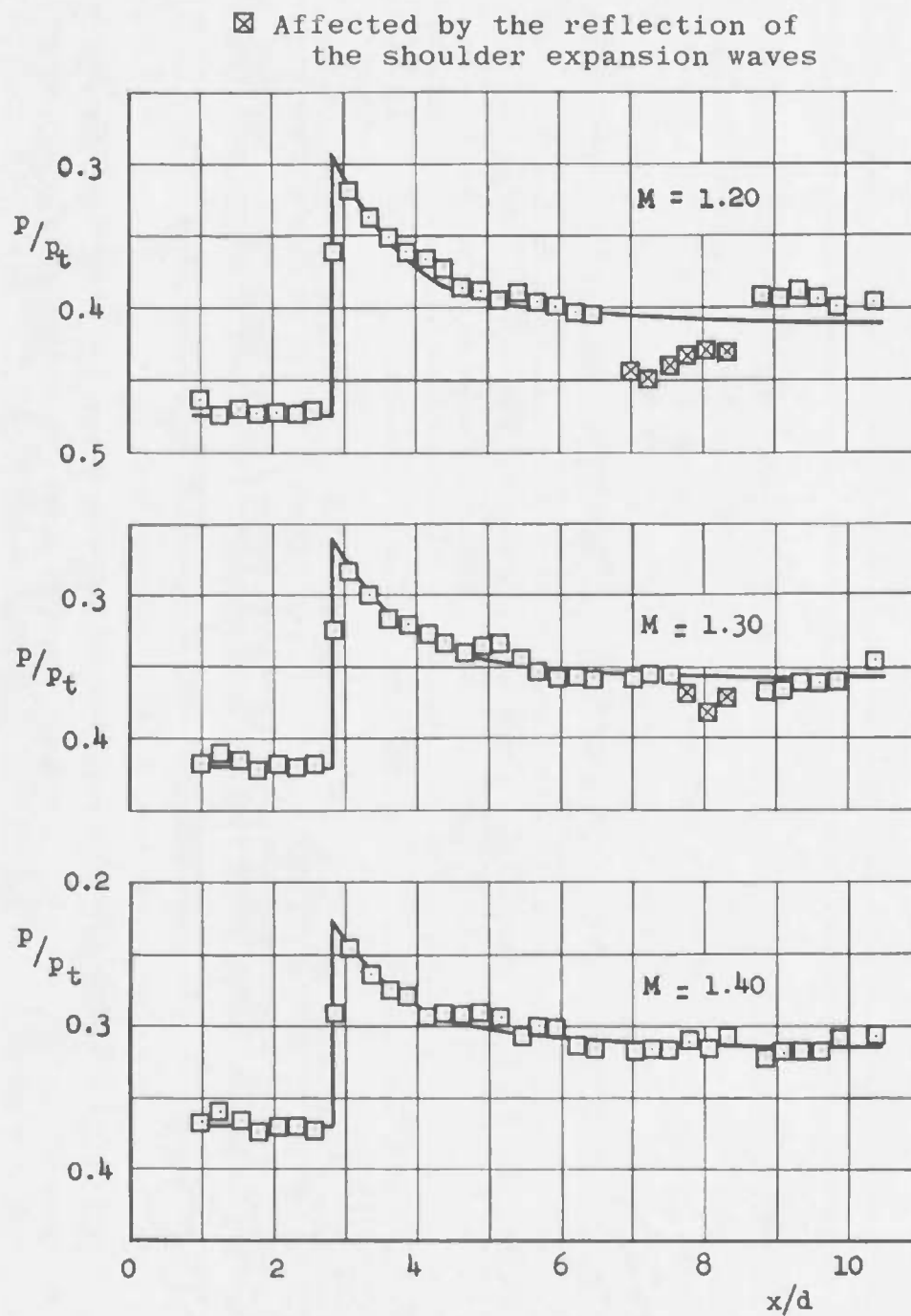
Fig. 12 Body Pressure Distributions on a 2-Percent Blockage, Cone-
Cylinder Model with Modified 10-Percent Slotted Hole Walls

Fig. 12 Concluded

a. Normal Hole Wall
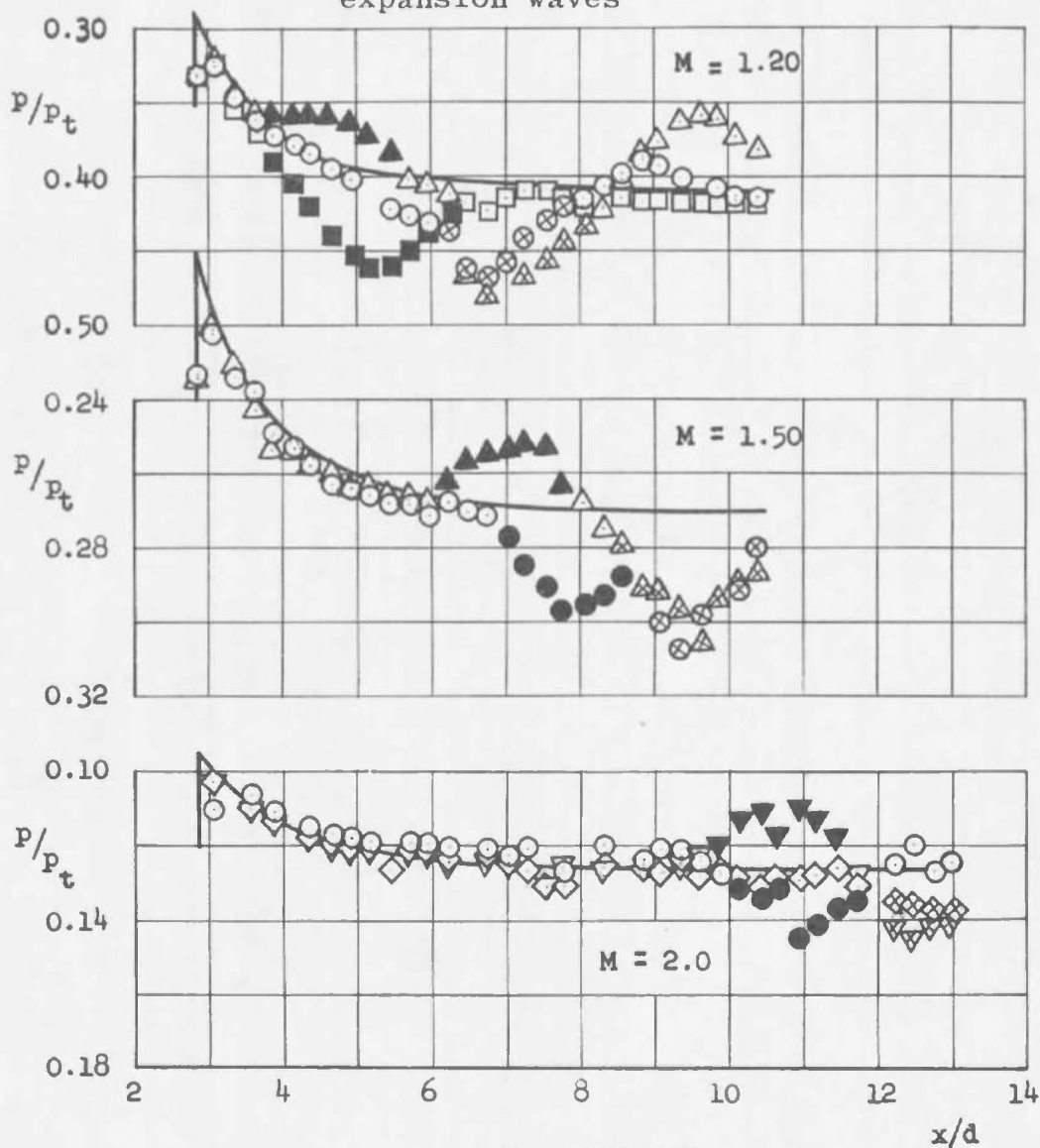
Fig. 13 Effect of Wall Porosity on Body Pressure Distributions of a 2-Percent
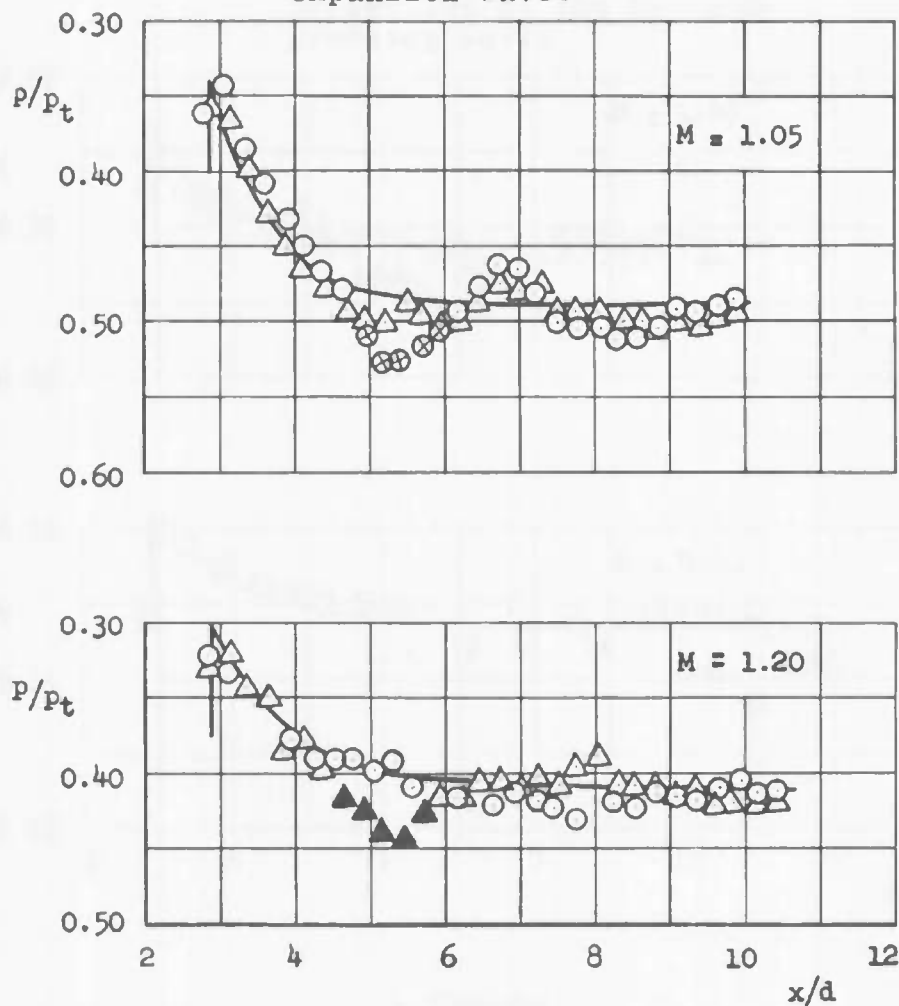Blockage, 20° Cone-Cylinder Model

b. Slanted Hole Wall

Fig. 13 Continued
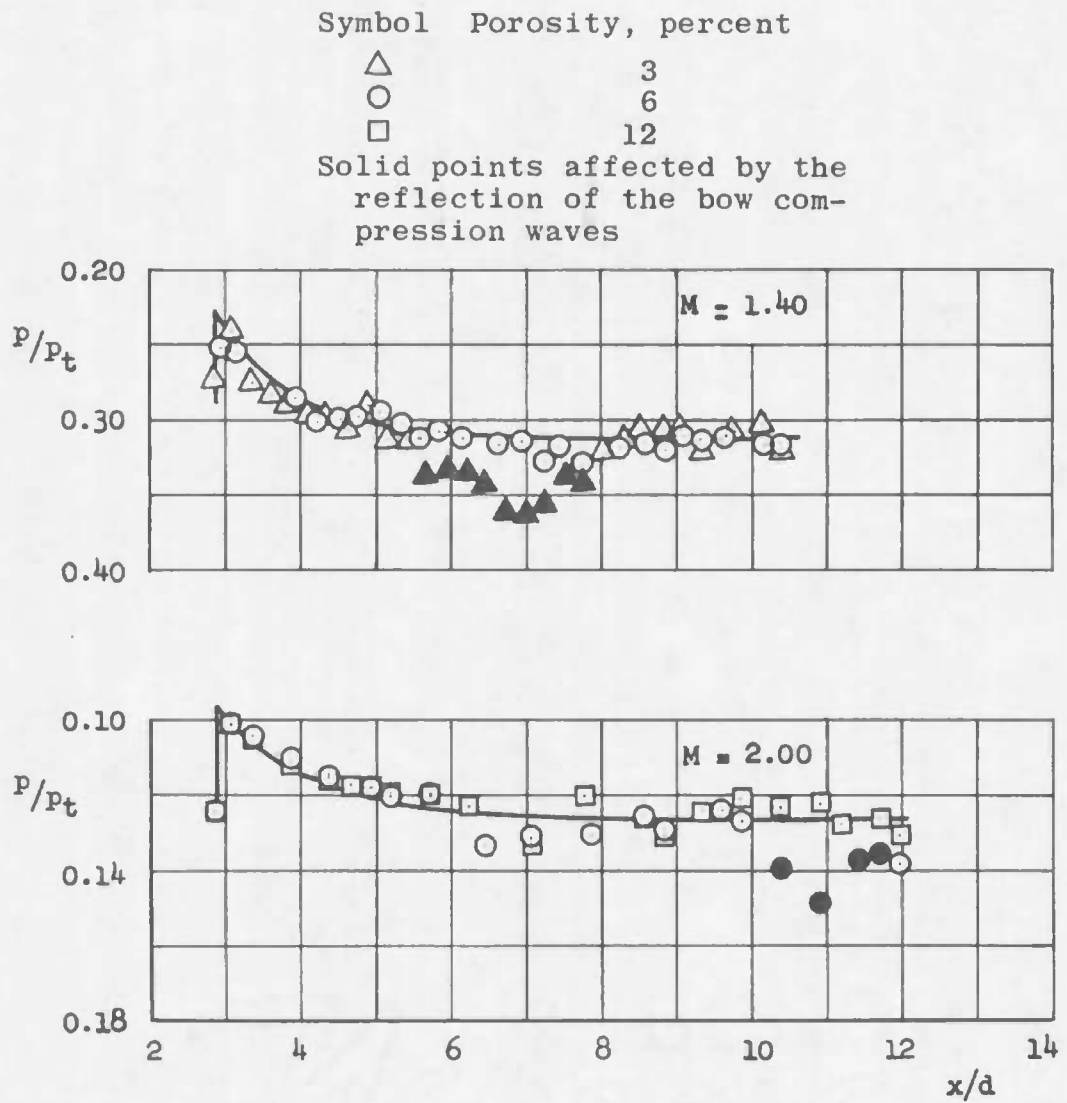
b. Concluded

Fig. 13 Concluded

Symbol   Wall Angle, min
   ○   −20
   □   0
   △   +30

p/p_t

a. Slanted Hole Wall
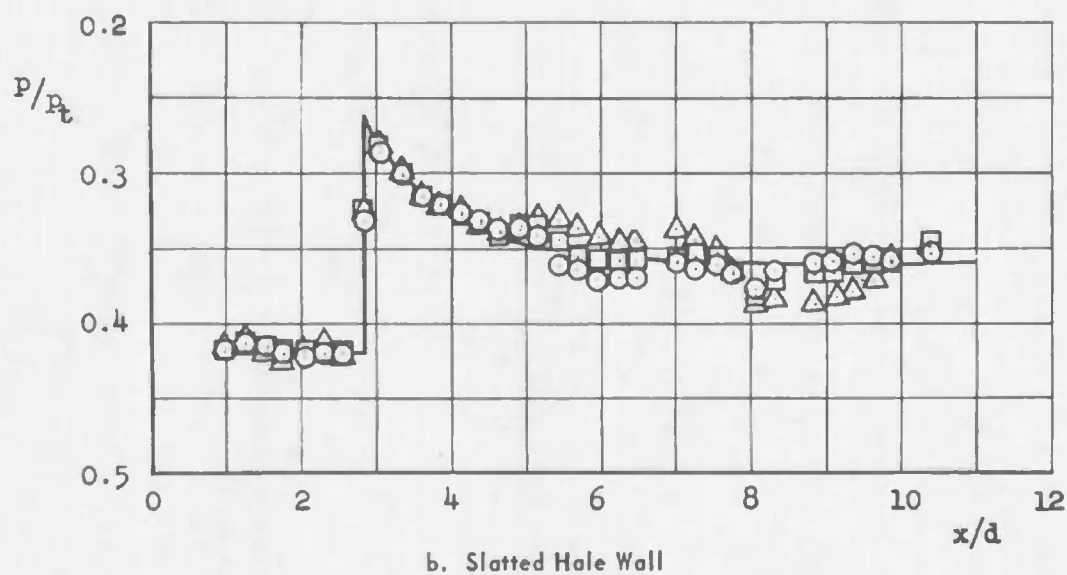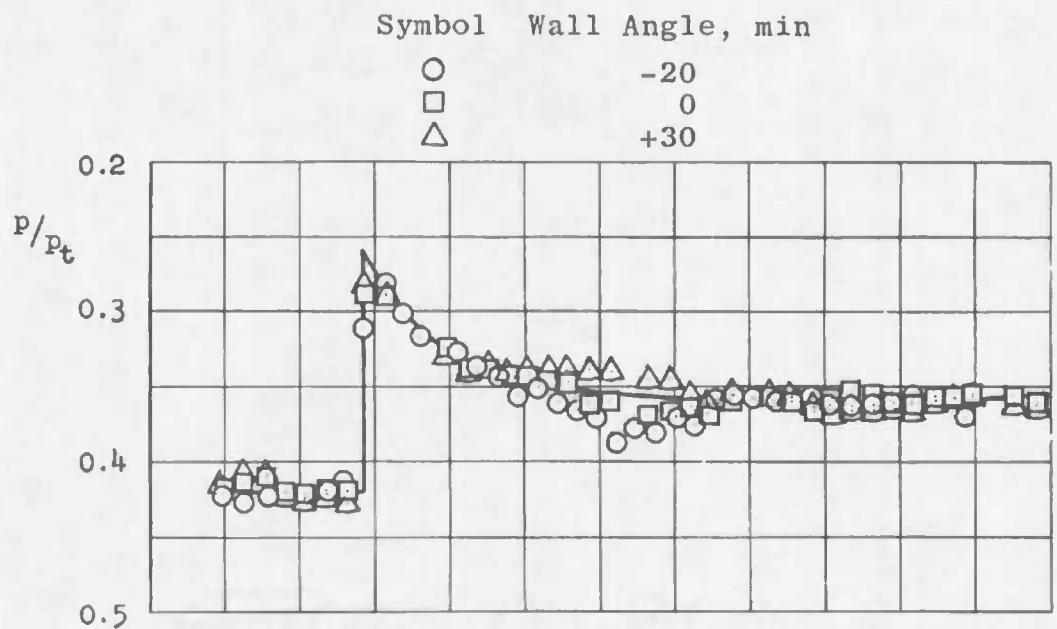
p/p_t

x/d

b. Slatted Hole Wall

Fig. 14 Effect of Wall Angle on the Body Pressure Distributions of a 2-Percent
Blockage, 20° Cone-Cylinder Model at M = 1.30